Two identical long-period fiber gratings (LPFGs) are difficult to produce in practice, notably for CO$_2$-laser or arc-discharge induced LPFGs. So it is meaningful to study the spectrum evolution of cascaded LPFGs with some deviation, named “mismatching” LPFGs. Theory and experiment demonstrate that the upper envelope of the fringe pattern is intrinsically curved but less dramatically than the lower envelope. Bending the grating pair to introduce proper cladding-mode loss can improve the contrast of the fringe pattern at a desired wavelength, which indicates that cascaded mismatching LPFGs can be used as high-quality comb filters or fiber sensors. © 2012 Optical Society of America

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1. Introduction

Long-period fiber grating (LPFG) written in single-mode fiber (SMF) is a band-rejection filter that couples light from the core mode (LP$_{01}$) into selected codirectional cladding modes (LP$_{0m}$), generating a series of attenuation discretely distributed in the transmission spectrum. If one LPFG is connected with a length of grating-free region with the coating layer removed, coupled LP$_{0m}$ mode and uncoupled LP$_{01}$ mode can propagate in fiber core and cladding at different velocities, respectively. If they encounter a second LPFG, the former will be recoupled into fiber core and interact with the latter, forming sharp interference fringe patterns. A pair of cascaded LPFGs functions as a Mach–Zehnder interferometer and is useful for many applications, ranging from a comb filter in optical communication [1] to optical sensor [2] and fiber laser [3]. Thus far, investigations on cascaded LPFGs have been broadly reported even including the behaviors of cascaded multiple LPFGs [4], but most of the investigations were developed on the premise that the same 3 dB LPFGs are cascaded. In such cases, the interference spectrum exhibits wide interferential bandwidth, a flat top, and high contrast, meeting the common requirements for a multichannel filter.

Although there are many techniques to fabricate LPFGs, such as mechanically pressing [5], electric-arc discharge [6], irradiation of ultraviolet (UV) [7], infrared femtosecond [8], or CO$_2$ laser [9–12], producing totally identical LPFGs on the same length of fiber is almost impossible. Consider the CO$_2$-laser method based on heating effect: first, it is not easy to get rid of the power or energy drift of the irradiation source during the grating fabrication, which is pronounced in the point-to-point writing style; and, second, because the LPFGs are used as sensors, a slight local environment disturbance on produced LPFGs may cause them to depart from their original states. As a result, most real cascaded LPFG pairs are composed of gratings with more or less of a deviation from each other, which are named “mismatching” LPFGs. Moreover, according to conventional viewpoints, a cascaded grating pair should be kept straight when it is used as a multichannel filter, because bending it will induce cladding-mode loss that deteriorates the spectrum, similar to the mismatching effect [13].
This paper establishes a theoretical model on the spectrum evolution of cascaded mismatching LPFGs and derives the explicit expressions of the upper and lower envelope of the interferential fringe pattern, respectively. With this model, our recent work has proved the upper envelope to be intrinsically curved, and in the same way we used it to form a special comb filter with individually variable channel transmissivities [14]. To our knowledge, the lower envelope of the cascaded mismatching LPFGs is specifically investigated for the first time in this paper. The profile of the lower envelope is more curved and sensitive than the upper envelope, also depending on the component LPFGs’ transmission spectra and the cladding-mode loss. There is an optimum value of the cladding-mode loss to achieve the largest contrast at a desired wavelength. In our experiment, by bending the grating pair to introduce proper cladding-mode loss, local high contrast can be realized and continuously tuned from 1520 nm to 1560 nm, which is especially valuable to optimize the performance of cascaded LPFGs induced by CO₂ laser. Our research indicates that mismatching or the bending effect does not always act as a drawback, but they can be utilized to improve the behavior of the multichannel filter and high-performance fiber sensor on the basis of cascaded LPFGs.

2. Principle of Cascaded Mismatching LPFGs

To lower the complexity of this discussion on the basis of conventional coupled-mode theory (CMT), the cascaded LPFGs in this paper are regarded as uniform gratings written on SMF with an identical period of Λ, so the resonant cladding-mode order is the same for the two gratings. Because generally the spectral range of interest is short, e.g., near 1550 nm, the separation between rejection-band centers is usually wider than the bandwidth. Then our calculation considers only the two-mode coupling between the LP₀₁ mode and a certain m-th order cladding mode, LP₀ₘ, which satisfies the well-known phase-matching condition that describes the “design wavelength,” λ₀, of the LPFG,

\[ \lambda₀ = (n_{co eff} - n_{cl eff}^m) \Lambda \equiv \Delta n_{eff} \Lambda \]  

where \( n_{co eff} \) and \( n_{cl eff}^m \) are the respective unperturbed effective indexes of LP₀₁ and LP₀ₘ mode and \( \Delta n_{eff} \) is their difference. The complex modal amplitudes of the two modes after passing through LPFG1 of length \( d₁ \) is given in a matrix form as follows [4,15]:

\[
\begin{bmatrix}
  a_{co} \\
  a_{cl}^m
\end{bmatrix}
= \exp \left( \frac{i \Delta n_{eff} d₁}{2} \right)
\begin{bmatrix}
  \exp \left( i \lambda₀ d₁ \right) & 0 \\
  0 & \exp \left( -i \lambda₀ d₁ \right)
\end{bmatrix}
\begin{bmatrix}
  t₁ \\
  r₁
\end{bmatrix}
\]

where \( \kappa₁ \) is the “ac” cross-coupling coefficient of LPFG1. If the refractive-index (RI) modulation is mainly constrained in fiber core, it can be simply given by [16]

\[ \kappa₁ = \frac{n_{co eff,1}}{\lambda}. \]

In Eq. (2.4), \( n_{co eff,1} \) is the average effective-index modulation on LP₀₁ mode, the essential parameter of an LPFG, induced in the grating formation; \( \lambda \) is the wavelength. Much of the literature has noticed that the respective propagation constants of LP₀₁ and LP₀ₘ mode in grating region were both treated in the same way as those in the grating-free region, \( \beta_{co} \) and \( \beta_{cl} \). In Eq. (2), however, \( \beta_{co} \) in LPFG1 is modified as follows:

\[ \beta_{co in 1} = 2\pi(n_{co eff} + \overline{n}_{co eff,1})/\lambda \]  

In this paper, the cascaded LPFGs are not necessarily 3 dB weak gratings. As a result, the resonance wavelength of LPFG1 must depart from its design wavelength, coinciding with the real observations in all experiments on LPFGs,

\[ \lambda_{res,1} = [1 + \Delta n_{co eff,1}/\Delta n_{eff}] \lambda_D \]  

Moreover, the LPFG detuning is defined as

\[ \delta \beta_{in 1} = \beta_{co in 1} - \beta_{co eff} - 2\pi/\Lambda \]

In Eq. (2), the matrix of \([1,0]^T\) represents the boundary condition that no cladding modes are incident to LPFG1.

If the SMF coating layer made of silicon resin is removed, the LP₀ₘ mode can also propagate in the grating-free region of length \( Lₘ \) as the residual LP₀₁ mode, and the modal amplitudes become

\[
\begin{bmatrix}
  t₂ \\
  r₂
\end{bmatrix}
\]

Here, we define

\[ t₁ = \cos s₁ d₁ + i\delta β_{in 1} \sin s₁ d₁ / (2s₁), \]

\[ r₁ = i₁ k₁ \sin s₁ d₁ / s₁, \]

\[ s₁ = \sqrt{k₁^2 + (\delta β_{in 1}/1)^2}, \]
\[
\begin{bmatrix}
    a_c(0, d_1 + L) \\
    a_c^m(d_1 + L)
\end{bmatrix} = \begin{bmatrix}
    \exp(i\beta_c L) & 0 \\
    0 & \alpha \exp(i\beta_c^m L)
\end{bmatrix}
\times \begin{bmatrix}
    a_c(d_1) \\
    a_c^m(d_1)
\end{bmatrix}, 
0 \leq \alpha \leq 1. \tag{3}
\]

In Eq. (3), \( \alpha \) is the bending-induced loss on LP_{0, m} mode, \( \alpha = 1 \) indicates no loss, and \( \alpha = 0 \) indicates complete loss [13]. When the two guided modes encounter LPFG2 of length \( d_2 \), the final modal amplitudes are obtained:

\[
\begin{bmatrix}
    a_c(D) \\
    a_c^m(D)
\end{bmatrix} = \exp\left(i\frac{\beta_c\text{in.} + \beta_c^m}{2}d_2\right)
\begin{bmatrix}
    \exp\left(i\frac{\beta_c}{2}d_2\right) & 0 \\
    0 & \exp\left(-i\frac{\beta_c}{2}d_2\right)
\end{bmatrix}
\begin{bmatrix}
    r_2 & r_2 \\
    t_2 & t_2
\end{bmatrix}
\begin{bmatrix}
    a_c(d_1 + L) \\
    a_c^m(d_1 + L)
\end{bmatrix}. \tag{4}
\]

where \( D = d_1 + L + d_2 \), and the definitions of other parameters are analogies to LPFG1. By calculating from Eq. (1) to (4), the core-mode transmission function of the general cascaded LPFGs can be written in a compact and meaningful expression in polar form:

\[
T(\lambda) = |a_c(0)|^2 = \frac{\sqrt{T_1(\lambda)T_2(\lambda)} \exp(i\Phi)}{-\alpha \sqrt{1 - T_1(\lambda)} \cdot \sqrt{1 - T_2(\lambda)}}. \tag{5.1}
\]

In Eq. (5), the small quantity and common factor on the right side of the equation is omitted, and the phase \( \Phi \) is

\[
\Phi = \tan^{-1}[\delta\beta_{in, 1} \cdot \tan(s_1 d_1)/(2s_1)] \\
+ \tan^{-1}[\delta\beta_{in, 2} \cdot \tan(s_2 d_2)/(2s_2)] + (\beta_c - \beta_c^m) L. \tag{5.1}
\]

\( T_1(\lambda) \) and \( T_2(\lambda) \) are the core-mode transmission functions of LPFG1 and LPFG2, respectively, which are positive real numbers, given by

\[
T_1(\lambda) = \cos^2 s_i d_i + (\delta\beta_{in, i}/2s_i)^2 \sin^2 s_i d_i, \\
\times (i = 1, 2), \quad T_1(\lambda) \leq 1. \tag{5.2}
\]

where we use the math relation that \( 1 - T_1(\lambda) = k^2 \sin^2(s_i d_i)/s_i^2 \). The upper and the lower envelope surrounding the fringe pattern of the cascaded LPFGs then are obtained when the phase factor in Eq. (5), \( \exp(i\Phi) \), is equal to \( \mp 1 \):

\[
T^{\text{upp}}_{\text{en}}(\lambda) = \left(\sqrt{T_1(\lambda)T_2(\lambda) + \alpha \sqrt{1 - T_1(\lambda)} \cdot \sqrt{1 - T_2(\lambda)}}\right)^2, \tag{6}
\]

\[
T^{\text{low}}_{\text{en}}(\lambda) = \left(\sqrt{T_1(\lambda)T_2(\lambda) - \alpha \sqrt{1 - T_1(\lambda)} \cdot \sqrt{1 - T_2(\lambda)}}\right)^2. \tag{6.1}
\]

From Eq. (6), we can readily deduce an inequality about the upper envelope:

\[
T^{\text{upp}}_{\text{en}}(\lambda) \leq \left[\sqrt{T_1(\lambda)T_2(\lambda) + \alpha (1 - \sqrt{T_1(\lambda)T_2(\lambda)\right)}\right]^2 \leq 1, \tag{7}
\]

where the equal sign holds only for \( T_1(\lambda) = (\lambda) ) \), \( \alpha = 1 \). That is, the upper envelop of cascaded general LPFGs is intrinsically curved, deviating from unity, except in the ideal condition in which the component LPFGs are identical and there is no cladding-mode loss. This theoretically explains why there are always spectral differences between the reality and theory in which cladding-mode loss and mismatching effect are usually neglected.

On the basis of our theoretical modal, we calculate the transmission spectrum of cascaded mismatching LPFGs with deviation in the period amount of \( N \) and \( \Delta n_{co, eff} (d = N \cdot \Lambda) \), for the moment overlooking the cladding-mode loss. In calculation, \( \Lambda \) is fixed as 625 \( \mu \)m, and other raw parameters are listed in Table 1. Because the LPFGs in our experiment were induced by CO_2 laser, the sign of \( \Delta n_{co, eff} \) is negative and the absolute value is estimated to be about the order of \( 10^{-5} \) [17,18]. From Eqs. (5.1)–(7), the calculated transmission spectrum of the cascaded LPFGs, \( T \), is plotted in Fig. 1, along with \( T_1, T_2, T^{\text{upp}}_{\text{en}}, \) and \( T^{\text{exp}}_{\text{en}} \). The transmission spectra of the two gratings, denoted by black dash and dash-dot lines in Fig. 1, are different from each other in that the resonant wavelengths and lowest transmissivities for them are 1555 nm versus 1546.8 nm and 0.67 versus 0.19 (in absolute units), respectively. Thus, according to our definition, they are mismatching LPFGs. The red upper envelope of the
interference fringe pattern is slightly curved as predicted. This simulation resembles the real spectra of cascaded LPFGs presented in much of the literature.

Generally, ideal cascaded LPFGs designed for multichannel filters should have transmission spectra with flat tops and large contrasts, as plotted in Fig. 2, because large contrast performs in favor of high channel isolation or low cross talk in communication systems. This perfect filter consists of two 3 dB gratings, e.g., two identical LPFGs with lowest transmission of 0.5 at 1551.2 nm, as shown in Fig. 2. All kinds of probable disturbances are almost inevitable during and after the grating fabrications, notably for the CO$_2$-laser or arc-discharge method, and thus in actuality, cascaded mismatching LPFGs, rather than matching LPFGs, mostly take place. The mismatching effect was regarded as a flaw, bad for the performance of a comb filter. Nevertheless, on the basis of our model, it is still possible to enhance the contrast for cascaded mismatching LPFGs. As suggested in Fig. 1, the curvature of the lower envelope varies much more steeply than the upper envelope. In mathematics, this curvature is caused by the logarithm coordinate and the “minus” sign between the two terms on the right side of Eq. (6.1). So, if the overall fluctuation of the upper envelope is small, the spectral contrast around a specific wavelength will be maximized when the lower envelope function becomes zero (in linear coordinate), i.e., set $T_{\text{low}}(\lambda) = 0$, from Eq. (6.1),

$$\alpha = \frac{T_1 T_2}{(1 - T_1)(1 - T_2)}$$

(7.1)

Eq. (7.2) takes into consideration $0 \leq \alpha \leq 1$. Theoretically, for cascaded mismatching LPFGs, introducing moderate cladding-mode loss by bending the grating pair is able to adjust the high-contrast region to a desired wavelength. According to Eq. (7.2), only when the transmissivities of two component LPFGs are both 0.5, or at least when one of them is smaller than 0.5, can the contrast reach be maximized. Notice that for a single LPFG, the stronger the grating, the smaller the lowest transmissivity.

Reusing the parameters in Table 1 (except $\alpha$ becomes 0.73), the resultant spectrum is plotted in Fig. 3. As shown, although the upper envelope still deviates from unity, the fluctuation is not severe if viewed in a short spectral range, whereas the large-contrast region is adjusted to about 1550 nm, similar to the case in Fig. 2. If such a grating pair is used as a comb filter, it will work as an analog of ideal cascaded LPFGs, except for a slightly larger insertion loss.

Some recent studies extend conventional CMT to coupled local-mode theory (CLMT) to analyze strongly modulated LPFGs [19,20]. Calculation of the mode-coupling process based on CLMT is more accurate than conventional CMT, if LPFGs are inscribed by CO$_2$ laser or arc discharge in which asymmetrical structural and index changes cause modifications of the mode fields, the propagation constants, and the coupling coefficients. In other words, in grating region, $\delta n_{\text{eff}}$ is not a constant confined in the fiber core, but rather it is a complicated azimuthal, radial, and longitudinal variable across the fiber core and cladding. Thus, in the strict sense,

$$T_1 + T_2 \leq 1.$$  

(7.2)

Fig. 1. (Color online) Simulated transmission spectra of cascaded mismatching LPFGs (in dB units) and the component LPFGs (in absolute units), along with the upper and lower envelope.

Fig. 2. (Color online) Simulated ideal transmission spectrum (in dB units) with flat upper envelope and high contrast, composed of cascaded two 3 dB LPFGs (in absolute units).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$N$</th>
<th>$L$</th>
<th>$m_{\text{cl,eff}}$</th>
<th>$\alpha$</th>
<th>Cladding Radius</th>
<th>Core Radius</th>
<th>$n_{\text{co,eff}}$</th>
<th>$n_{\text{d,eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPFG1</td>
<td>8</td>
<td>30 cm</td>
<td>$-6 \times 10^{-5}$</td>
<td>1</td>
<td>62.5 µm</td>
<td>4.1 µm</td>
<td>1.465125</td>
<td>1.462567</td>
</tr>
<tr>
<td>LPFG2</td>
<td>11</td>
<td>$-8 \times 10^{-5}$</td>
<td></td>
<td>0.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
for a single LPFG, all the mode-coupling relevant parameters defined in Eqs. (2) and (4), as well as the resultant depths or resonant wavelengths of rejection bands, should be modified to be polarization dependent. Moreover, mode couplings between LP$_{01}$ mode and asymmetric cladding modes (LP$_{1m}$) need consideration, if necessary. All the realistic and complicated effects in a single LPFG only affect the specific expressions of $T$ and $\Phi$ in Eqs. (5.2) and (5.1). If they are obtained by experiment combined with numerical calculation as in Jin et al. [19] and substituted into Eq. (5), the following formulas that describe the overall behaviors of cascaded gratings, including the upper and lower envelope, still stand, i.e., our conclusions on cascaded mismatching LPFGs are still effective.

3. Experiment Result and Discussion

Various point-to-point writhing methods have been used to fabricate LPFGs. Among them, irradiating fiber with a CO$_2$ laser to induce $\delta n_{co,eff}$ is a remarkable alternative for its distinct advantages, such as high flexibility and high writing efficiency, and for its lack of restriction on fiber type, high spectrum stability, and low insertion loss. In our experiments, all LPFGs were produced by line-focused and long-pulse CO$_2$ laser, which was driven by a stepping motor. A detailed description of our simple and low-cost setup was given in Liu et al. [11]. To weaken the asymmetric mode-coupling effect, following the principle presented in [11], we use a small-spot (120 $\mu$m) and comparatively short-pulse (200 ms) method to write the LPFGs under a constant and small tension provided by a 18 g weight, so the frozen-in stress is negligible [21]. Although the LPFGs became a little soft, because of the glass-structure change that resulted from the heating of the CO$_2$ laser, no obvious physical deformations were observed around the grating region under a microscope (magnification of 40 times). Because the CO$_2$ laser intensity is not too large, the strong perturbation effect is not significant in our LPFGs. The coating layer of the whole cascaded LPFGs needs removing and is quite fragile. It two LPFGs were produced in two sections of SMF and then spliced together afterward, it would be not convenient for either operating or controlling the LPFGs’ separation, which determines the spectral fringe spacing [22]. Therefore, we first wrote LPFG1, mechanically removing the jacket on the grating-free region as well as the next grating region, and then wrote LPFG2 in the same section of SMF. The disadvantage of this approach was that the optical spectral analyzer (OSA) could not individually measure the transmission spectrum of LPFG2. In addition, an erbium-doped fiber amplifier (EDFA) is used as the wideband source, from which unpolarized amplified spontaneous emission (ASE) light is incident to the grating pair and then monitored by the OSA in real time.

In our first pair of cascaded LPFGs, two gratings separated by 24.2 cm were produced with intended differences, i.e., the grating lengths and CO$_2$-laser powers were 7.5 mm and 11.25 mm, and 2.7 W and 2.3 W, respectively, whereas the periods were both 625 $\mu$m. When the grating pair is kept straight as usual, the measured interference spectrum looks unfavorable, as shown in Fig. 4, with an irregular upper and lower envelope along with a low contrast smaller than 7.5 dB. The reason for this irregularity is that LPFG2 is quite different from LPFG1. Next, these cascaded LPFGs were put on a simple bending-test setup, as shown in Fig. 5. The ends of the grating pair are clamped by two fiber holders that are adhered to two manual linear stages. When one of the linear stages moves inward, the grating pair tends to bend naturally along a fixed direction because of the slightly softened grating regions. During the bending test, the transmission spectrum of the cascaded mismatching LPFGs varies dramatically, mainly because of the introduced cladding-mode loss based on our model. Contrary to the previous viewpoint that bending always degrades the performance of cascaded LPFGs, in our experiment, bending improved the contrast of cascaded mismatching LPFGs.

Fig. 3. (Color online) Simulated high-contrast spectrum of cascaded mismatching LPFGs with proper cladding-mode loss.

Fig. 4. (Color online) The unfavorable transmission spectrum of cascaded mismatching LPFGs without bending.
With proper bending adjustments, local high-contrast fringe patterns, continuously tunable in C-band, were obtained. Figs. 6(a)–6(d) present four selected results from 1530 to 1560 nm, in which the maximum contrasts have reached 16 dB, 16 dB, 21 dB, and 11 dB, respectively. These results exhibit remarkable improvements brought about by bending above the average level of cascaded LPFGs produced by CO\textsubscript{2} lasers shown in other literatures. Therefore, even if mismatching LPFGs are cascaded, they are still possible to form a high-contrast comb filter around a certain wavelength of interest by bending the grating pair.

When \( s \), the displacement of the moveable fiber end read from the micrometer, is converted to curvature through [23]

\[
c = \frac{1}{R} \approx \sqrt[3]{\frac{24(s - s_0)}{L^3}},
\]

the relationship between the maximum-contrast wavelength \( \lambda_p \) and curvature \( c \) can be plotted in Fig. 7. Here, \( R \) is the radius of the bent grating pair; \( s_0 \) is the original reading; and \( L = 28 \) cm is the length of the bent segment between two fiber holders. The polynomial fitting of \( \lambda_p (\text{nm}) \) with respect to \( c (\text{m}^{-1}) \) is

![Fig. 5. (Color online) The simple setup for cascaded LPFGs bending test.](image)

![Fig. 6. (Color online) (a)–(d) Tunable local high-contrast spectra by bending cascaded mismatching LPFGs.](image)
Thus, this pair of cascaded mismatching LPFGs hopefully can be used as a high-sensitive curvature sensor. Compared with the sensor based on a single LPFG, fine interference fringes in the transmission spectrum of cascaded LPFGs can enhance the sensing resolution and sensitivity, for the bandwidth of an individual fringe can be much narrower than that of a single LPFG.\(^2\)

Because a short single LPFG has a wide rejection band, two short LPFGs can generate a wideband comb filter. Thus, we fabricated a second grating pair with two short LPFGs separated by 25 cm. The lengths and CO\(_2\)-laser powers were kept consistent this time, 3.75 mm and 2.4 W, respectively, and each writing point was exposed twice. When LPFG2 was written, and the grating pair was kept straight, the fringe pattern was still not of high quality. This result indicates that they are still mismatching LPFGs, which resulted from the inevitable power drift of CO\(_2\) laser and the radiation-mode loss in the grating regions. We conducted the bending test afterward and again found a significant spectral improvement, as shown in Fig. 8(a). From 1520 nm to 1560 nm, the top fluctuation is smaller than 1.2 dB and most contrasts are around 12–15 dB. The measurable spectral range is limited by the EDFA emission bandwidth. This result is not worse than the average performance of cascaded LPFGs written by UV light \(^1\), the stability of which is generally better than CO\(_2\) laser. Moreover, a small bending on the grating pair can make a channel-finely-tunable effect, as illustrated in Fig. 8(b), which is meaningful for a comb filter when used in a communication system to match the desired channel or in multiwavelength fiber lasers to adjust laser wavelengths.

According to Eq. (7.1), there are two ways to adjust the contrast around a certain wavelength: one is varying the transmission spectra of the component LPFGs, and another is introducing appropriate cladding-mode loss. Bending the grating pair is actually a mixture of these two methods. If the impact of cladding-mode loss is greater than that of the transmissivity variation of an individual LPFG during bending, our method still works. Theoretically, tuning the cladding-mode loss by controlling the RI surrounding the grating-free region (e.g., by chemical method instead of bending the grating pair), can avoid the transmissivity variation of component LPFGs. As examined during our experiments, properly bending rather than keeping straight indeed improves the performance of the grating pair, for as long as Eq. (7.2) is satisfied at that wavelength, there is always an optimal curvature to obtain high contrast. Some intrinsic defects of CO\(_2\)-laser induced LPFGs, however, limit further improvement on the contrast in our experiment, like polarization-dependent loss and asymmetric mode coupling. Even for cascaded UV-induced LPFGs, we believe that the spectral performance can be improved with cooperation of fine bending, because ideal matching LPFGs are almost impossible to produce.

\[
\lambda_p = 1527.57 + 4.04c + 107c^2. 
\]

Fig. 7. (Color online) Maximum-contrast wavelength versus curvature during bending of the grating pair.

Fig. 8. (Color online) (a) Wideband comb spectrum with comparatively flat top and high contrast by bending cascaded short LPFGs. (b) The channel-finely-tunable effect via small bending on the grating pair.
4. Conclusion

We have studied the spectrum evolution of cascaded mismatching LPFGs, including the general case in reality, in theory, and in experiment. Our model theoretically explains why the upper envelope of the fringe pattern is intrinsically curved; however, the lower envelope exhibits a much steeper curvature that is sensitive to the component LPFGs' spectra and cladding-mode loss. The practical meaning of our work is as follows: for the comb filter made up of cascaded mismatching LPFGs, the contrast can be improved around a certain wavelength by bending the grating pair to introduce proper cladding-mode loss; and this effect can also be utilized in bend sensing. In experiment, we obtained local high-contrast spectra that are continuously tunable, and wideband comb spectrum of high quality from 1520 nm to 1560 nm, as well as the finely tunable effect. The results are valuable for the application of CO\textsubscript{2}-laser or arc-discharge induced LPFGs.

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