

Linear and quadratic dispersion characterization of millimeter-length fibers and waveguides using common-path interferometry

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We measured linear and quadratic dispersion on millimeter-length fibers, waveguides, and nanowires based on common-path spectral interferometry. We obtained the linear dispersion parameter, β' , with a relative precision of 1.45×10^{-4} , and extracted the quadratic dispersion parameter, β'' , from the Taylor expansion of β' . β'' values show a discrepancy of $<1\%$ when compared with simulation as well as with measurement results obtained by a conventional Michelson interferometer. Using this method, we experimentally confirmed the sign inversion of the group velocity dispersion of AlGaAs nanowires for what is believed to be the first time. © 2007 Optical Society of America
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Dispersion characterization of short fibers and waveguides is desirable to the design of fiber-based and integrated photonic devices such as nanowires [1,2] and thermally poled twin-hole fibers [3] for non-linear optics applications. Realizing such components requires a detailed knowledge of the device's dispersion. Often, lengths used in these applications are of the order of millimeters, and therefore interferometric techniques, either temporal [4] or spectral [5,6], are favored. In spectral interferometry, fringes are produced by the interference of broadband light after propagating through a test path containing the device and a reference path. The spectral phase can be extracted from the fringe pattern, and higher-order dispersion can be directly derived. Since the variation of the spectral phase is small for short devices, accurate extraction of higher-order dispersion on millimeter-length devices has not been reported. Quadratic dispersion can be directly measured by employing a *balanced* dual-arm interferometer [5]. Given the limited bandwidth of the available sources, these interferometers would require the device to have a large dispersion-length product, rendering them impractical for mm-length devices.

In this paper, we present a simple common-path interferometric technique to measure linear and quadratic dispersion parameters on a twin-hole fiber, an AlGaAs waveguide, and nanowires, all of which are millimeters in length. Our technique is based on extremely accurate measurement of linear dispersion from the spectral Fabry-Perot fringes generated by the reflections from both facets of the sample. The high accuracy is achieved using a moving spectral window, and the linear dispersion at the central wavelength of the window is obtained using Fourier analysis. As a result, measurement precision of 1.45×10^{-4} is achieved, which allows for accurate extraction of the quadratic dispersion. Though common-path interferometers have been used in many applications [7], it is to our knowledge the first time that

common-path interferometry is used for quadratic dispersion measurement.

The essential element of this technique is to rely on the highly precise measurement of the linear dispersion so that higher-order dispersion parameters can be extracted accurately. The experimental setup (Fig. 1) consists of a broadband source, a circulator, and the cleaved sample under test. Light from the broadband source is launched into the sample through the circulator and an angle-cleaved connector, which eliminates the reflection from the connector-air interface. The Fabry-Perot interference fringe pattern produced by multiple reflections from both facets of the sample is recorded on the optical spectrum analyzer.

To extract as accurately as possible the linear dispersion parameter, β' , defined as the first derivative of the propagation constant with respect to wavelength, we divide the total bandwidth into a number of overlapping wavelength windows (subbands) and assume a fixed fringe period in each subband. This assumption is valid when $\Delta\lambda_j \ll 2\beta'(\lambda_j)/\beta''(\lambda_j)$, where $\Delta\lambda_j$ and λ_j are the width and the center wavelength of the j th subband, respectively. Under this assumption, β' at λ_j can be measured either directly from the av-

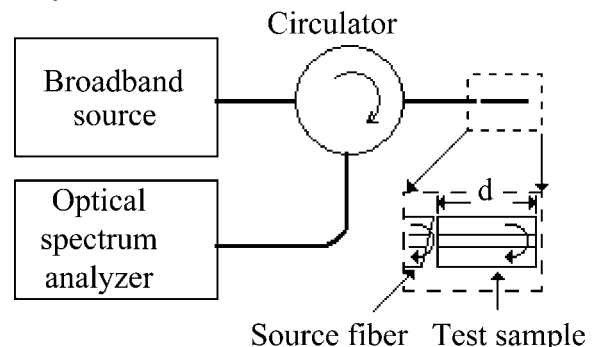


Fig. 1. Experimental setup of the single-arm interferometer for measuring the dispersion of fiber waveguide samples.

84 erage fringe period L_j ,

$$85 \quad \beta'(\lambda_j) = \beta'_j = \frac{\pi}{L_j d}, \quad (1)$$

86 or through Fourier analysis. Fourier series expansion
87 of the normalized Fabry–Perot intensity is

$$88 \quad \frac{I_j(\lambda)}{I_{j,\max}} = 1 - [a_0 + a_1 \cos(2(\lambda - \lambda_j)\beta'_j d) \\ 89 \quad + a_2 \cos(4(\lambda - \lambda_j)\beta'_j d) + \dots], \quad (2)$$

90 where, a_0 , a_1 , and a_2 are the expansion coefficients;
91 $I_{j,\max}$ is the maximum intensity in the j th band; and d
92 is the length of the waveguide. The Fourier trans-
93 form of Eq. (2) gives a series of peaks, and β'_j can be
94 measured directly from the index of the first peak,
95 $m_{p,j}$, as follows:

$$96 \quad \beta'_j = \frac{\pi m_{p,j}}{\delta\lambda M d}, \quad (3)$$

97 where M is the total number of samples in the Fou-
98 rier domain and $\delta\lambda$ is the wavelength sampling step.
99 Both methods return β' across the total wavelength
100 range with a coarse wavelength resolution that
101 equals the separation between the centers of the sub-
102 bands. β'' at each wavelength, λ_j , is calculated by fit-
103 ting $\beta'(\lambda)$ to a second-order polynomial around λ_j ,
104 and $\beta''(\lambda_j)$ equals the linear term coefficient. The
105 group effective index N_g , dispersion coefficient (D),
106 and group velocity dispersion (GVD) can be directly
107 calculated from β' and β'' as follows:

$$108 \quad N_g = -\frac{\lambda^2}{2\pi} \beta', \quad \text{GVD} = \frac{\lambda^3}{(2\pi c)^2} (2\beta'' + \lambda\beta'''), \quad (4)$$

109 where $D = -(2\pi c/\lambda^2)$ GVD. We used this method to
110 measure the dispersion parameters on three
111 samples: a 6 mm long twin-hole fiber, a 2.88 mm long
112 AlGaAs waveguide, and a set of Al_{0.2}Ga_{0.8}As nano-
113 wires of various widths and lengths. The fiber sample
114 consisted of a 4.5 μm radius Ge-doped silica core be-
115 tween two 45 μm radius air holes. The waveguide
116 consisted of a 1.5 μm Al_{0.18}Ga_{0.82}As core layer, sur-
117 rounded by Al_{0.24}Ga_{0.76} cladding layers (1.5 μm above
118 and 4.0 μm below), grown on a GaAs substrate with a
119 3.5 μm wide and 2 μm deep ridge. The nanowire
120 samples had lengths of 0, 300, 600, and 1000 μm , and
121 the core height was 500 nm. The wires were fed by a
122 2 μm wide waveguide and a 150 μm long taper. The
123 full structure was 2.4 mm long.

124 We estimate the appropriate subband widths, as-
125 suming $\Delta\lambda$ is two orders of magnitudes less than the
126 β' to β'' ratio and using Eq. (4). For the fiber sample,
127 we used the D and N_g values of the SMF-28 fiber. For
128 waveguide/nanowire samples, we used the effective
129 index method. As a result, the estimated maximum
130 subband width is 4.17 nm for the fiber sample and
131 11.85 nm for the waveguide and nanowires. Hence, in
132 all the measurements we used a 3 nm subband
133 width.

134 The sources used in our measurements were an
135 erbium-doped-fiber amplified spontaneous emission
136 source (50 nm bandwidth) for the twin-hole fiber and
137 an Agilent 83437A broadband source (250 nm) for the
138 waveguide sample and nanowires. For all cases, we
139 found there was no need for phase stabilization dur-
140 ing measurement. The average fringe period L_j of
141 each subband is measured using a peak-finding tech-
142 nique after smoothing the data (moving average).
143 This results in a β' measurement standard deviation
144 of 0.025% for the fiber sample and 0.052% for the
145 waveguide sample. A more accurate result can be
146 achieved using Fourier analysis, where a fast Fourier
147 transform technique is applied. The resulting stan-
148 dard deviations are 0.017% for the fiber and 0.014%
149 for the waveguide, roughly a factor of 2 improvement
150 in standard deviation over the direct measurement of
151 the period. The multiple facets' reflections have no ef-
152 fect on the Fourier analysis, as only the first peak is
153 considered.

154 Figures 2(a) and 2(b) depict the measured β' and
155 β'' respectively, for the twin-hole fiber using the Fou-
156 rier analysis. These results show a good agreement
157 (difference less than 0.45%) with those obtained from
158 balanced Michelson interferometer measurements
159 with a 10 cm piece of the same fiber. The measured
160 dispersion parameters for the waveguide (Fig. 3)
161 show a good agreement with the simulated disper-

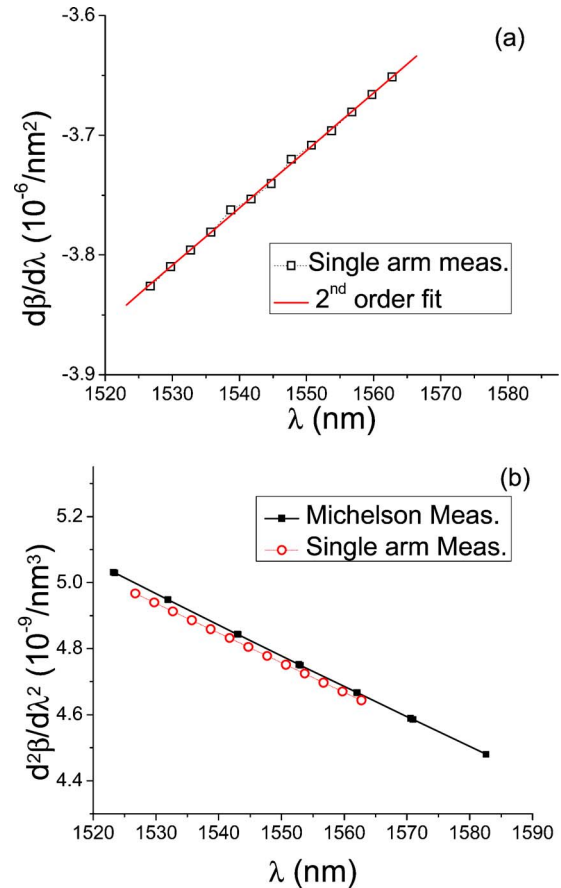
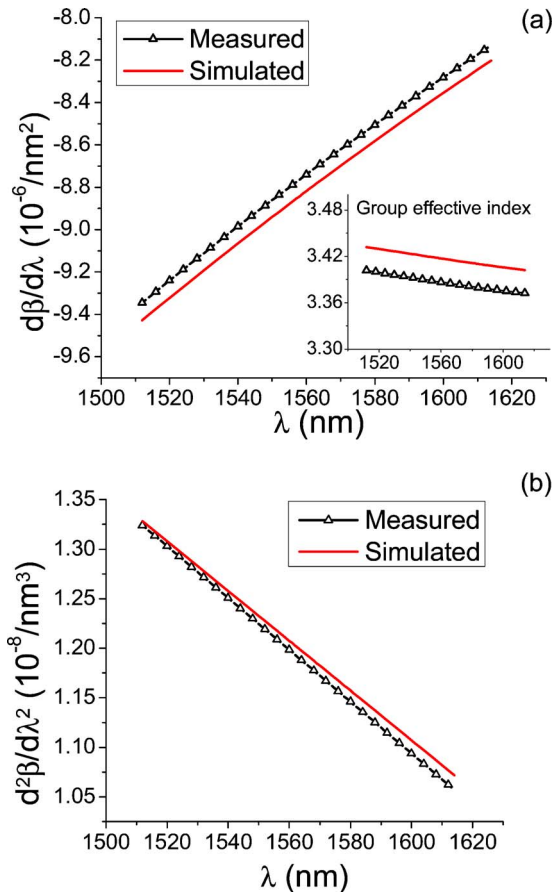
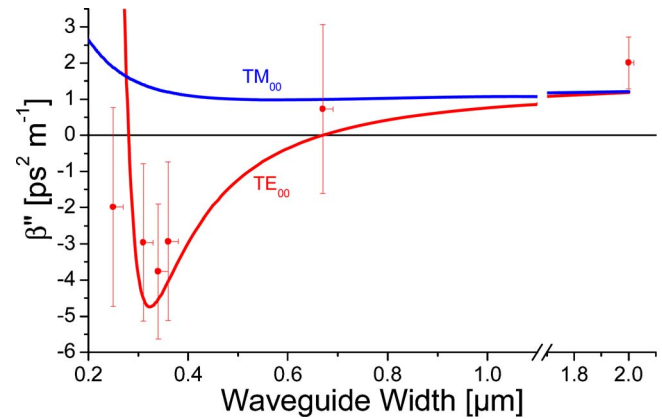


Fig. 2. (Color online) Measured β' (a) and β'' (b) for a 6 mm piece of twin-hole fiber compared with Michelson interferometer measurements of a 10 cm piece of the same fiber. Color: Online



Color: Online Fig. 3. (Color online) (a) Measured β' and N_g (inset) and (b) β'' compared with the simulated dispersion for a 2.88 mm AlGaAs ridge waveguide sample obtained using the effective index method.



Color: Online Fig. 4. (Color online) Measured (dots with error bars) and calculated GVD versus waveguide width at the wavelength of 1.55 μm .

first experimental demonstration of GVD inversion 186
in nanowires by direct measurement. 187

We have presented an interferometer technique for 188
the measurement of linear and quadratic dispersion 189
parameters (β' and β'') on short waveguide samples 190
using a common-path interferometer. The fiber-based 191
technique is simple and does not require active stabi- 192
lization. We applied this technique to a 6 mm long 193
twin-hole fiber, a 2.88 mm long AlGaAs waveguide, 194
and nanowires that exhibit GVD inversion. The high 195
accuracy and high resolution in β' were achieved by 196
dividing the working wavelength range into a number 197
of overlapping subbands and extracting the 198
fringe period using Fourier analysis. The standard 199
deviations of measured β' are 0.014% and 0.018% for 200
the waveguide and the fiber samples, respectively. 201
The extracted β'' had a better than 1% agreement 202
with the simulation result or with measurement re- 203
sults independently obtained using a balanced Mich- 204
elson interferometer. Finally, our results obtained on 205
the nanowires are believed to be the first direct ex- 206
perimental verification of GVD inversion in these 207
structures. 208

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162 sion using the effective index method [8], with dis- 163
crepancies of less than 0.9%. This can be attributed 164
to the uncertainties in the simulation parameters. 165
Using Eq. (6), the measured D and GVD at 1550 nm 166
are -1036.5 ps/nm.km and 1.32 ps²/nm, respectively, 167
which are close to the reported bulk Al_{0.2}Ga_{0.8}As pa- 168
rameters ($|D|=1000$ ps/nm.km and GVD= 1 ps²/nm) 169
[9]. The differences are due to waveguide dispersion 170
and the core material's being slightly different 171
(Al_{0.18}Ga_{0.82}As).

172 Finally, we apply our technique to AlGaAs nano- 173
wires and show that this structure exhibits strong 174
GVD inversion for submicrometer-wide waveguides 175
(around 400 nm in Fig. 4), which has been recently 176
predicted theoretically [1]. We used nanowires of 177
various lengths to calibrate out the dispersion of the 178
feed waveguides and the tapers. The calculated and 179
measured GVD at 1.55 μm show that, for waveguide 180
widths between 670 and 281 nm, the strong field con- 181
finement dominates the material dispersion and 182
leads to an inversion of the GVD of the TE mode. 183
Here, the vertical error bars of the measured data 184
points have been obtained by bootstrapping the mea- 185
sured fringe periods. This is to our knowledge the